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BEHAVIOR OF BOND UNDER DYNAMIC LOADING

by
Indravadan K. Shah

Supervised by
Robert J. Hansen

Sponsored by
DEFENSE ATOMIC SUPPORT AGENCY
NWER Subtask 13.105
Contract No. DA-49-146-XZ-061

March, 1963

MIT

DEPARTMENT
OF
CIVIL
ENGINEERING

SCHOOL OF ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge 39, Massachusetts

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PREFACE

This research was conducted in the Structures Division of the Department of Civil Engineering, under Contract DA-49-146-XZ-061 with the Defense Atomic Support Agency. The research was directed by Professor Robert J. Hansen and was carried out by the author.

Appreciation is extended to Dr. S. P. Mauch for his help in planning the initial phase of the project and to E. F. McCaffery, E. N. Brinkerhoff, R. J. Cronin and R. E. Brooks for their help in carrying out the tests.

Special thanks are due to the Defense Atomic Support Agency for sponsoring this research.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

LIST OF FIGURES

LIST OF TABLES

SUMMARY

OBJECTIVE

The main objective of this research is to study the bond behavior of reinforcing bars under dynamic loading, as influenced by the compressive strength of concrete and diameter of the reinforcing bars.

RESEARCH PROGRAM

This research program is the continuation of the previous research, conducted in the Structures Division of the Civil Engineering Department of M.I.T. in 1959. The present program has covered the following categories of tests:

I - Specimens with variation in the compressive strength of concrete. In this category, three different concrete strengths 2000 psi, 3500 psi and 6000 psi are used.

II - Specimens with the variation in the diameter of reinforcing bar. Three different bars #8, #10 and #14 are used.

CONCLUSIONS

These tests have indicated that (1) the static ultimate bond strength of concrete, for relatively large diameter reinforcing bars, is of the order of 0.5 to 0.6 f'_c , while the corresponding dynamic ultimate bond strength of concrete varies from 0.6 to 0.9 f'_c , depending upon the static compressive strength of concrete; (2) the static and dynamic ultimate bond stress "u" increases with increase in f'_c; (3) the ratio u/f'_c , for the values of f'_c between 2000 and 6000 psi is more or less constant for the static case. In the dynamic case, however, the corresponding u/f'_c ratio is not constant. It is much higher for the low strength concrete than for the high strength concrete; (4) the increase in bond strength under dynamic loads is higher for the low strength concrete compared to moderate or high strength concrete; (5) the static and dynamic ultimate bond stress decreases with increase in the diameter of reinforcing bars; and 6) the increase in the ultimate bond strength under dynamic loads seems to vary inversely with the diameter of the reinforcing bar.

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The main objective of this research is to study the bond behavior of reinforcing bars under dynamic loading, more specifically at rapid strain rates.

A research program, sponsored by the U. S. Atomic Energy Commission (Contract No. AT (29-2)-616), with the object of studying the bond behavior of reinforcing bars under dynamic loads, was conducted in the Civil Engineering Department of M.I.T. in 1959. The results of this program are published in a report[9]* entitled "Behavior of Bond under Dynamic Loading". The present program is the continuation of this previous research, with the object of determining the influence of certain parameters, such as concrete strength and diameter of reinforcing bars on the bond behavior of reinforcing bars under dynamic loading.

1.2 PREVIOUS WORK

Extensive literature is available on bond tests between concrete and steel, performed either by using pullout specimens or beams. It has been found that the pullout specimens represent with reasonable accuracy the bond conditions in reinforced concrete elements where bending is of the primary importance. (Refer Appendix - I).

Tests[1,4] have shown that bond strength, 1) is greater for deformed bars than plain bars; 2) increases with average height and bearing area of deformations; 3) decreases with the increasing ratio of shearing to bearing area of deformations; and 4) is unaffected by the pattern of the deformations.

It has been shown[2] that for plain bars, bond strength increases with the concrete strengths below 2000 psi, but above 2000 psi, the increase in bond strength is insignificant. Therefore, for all practical purposes, bond strength for plain bars is independent of compressive

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* Superscript numbers in parenthesis are references presented in Bibliography.

strength. For deformed bars, however, tests[7] have shown that at the same amount of slip bond stress increases with increasing concrete compressive strength.

The orientation of bars at the time of casting of concrete is also an important factor.[2,3] Bars oriented horizontally, will draw up water beneath them and a stiff concrete mix, as it settles, will draw away from the bar, resulting in poor bond.

Tests[5,8] have also indicated that the distribution of bond stress along the bar is such that it reaches its maximum almost immediately inside the effective bond length at loaded end and drops off towards unloaded end. At a length of 24 diameters, from the loaded end of the bar, bond stresses are practically zero. Therefore, with the increases in the bond length, resistance to the pullout of the bar does not necessarily increase.

The only information available on the bond behavior of reinforcing bars under dynamic loading is from the research done in the Structures Division of the Civil Engineering Department of M.I.T., as mentioned in Section 1.1. This research consisted of the testing of:

(1) Specimens with #6 bars embedded according to ACI Building Code.
(2) Specimens with #6 bars embedded 5".
(3) Specimens with #4 bars embedded 2", 3" and 4".
(4) Specimens with #6 bars with standard hooks.

All these specimens were tested for both static and dynamic loads, the dynamic load simulating an initial peak triangular loading. The results of this research indicate that, 1) local static bond strength may be as high as 0.75 f'_c and that under dynamic loading this strength increases to f'_c , 2) for all practical lengths of embedment of bars, steel failure is to be expected both under static and dynamic loading.

1.3 PRESENT RESEARCH PROGRAM AND ITS SCOPE

This program has covered following types of tests:

I. Specimens with the variation in the compressive strength of concrete. In this category three different concrete strengths, 2000 psi, 3500 psi, 6000 psi were used.

II. Specimens with the variation in the bar diameter. Three different bars #8, #10, and #14 were used.

Pullout specimens were used for the tests, both of static and dynamic loads. The dynamic load was of a triangular pulse type with a rise time of about 15 to 30 milliseconds. In both the above types the emphasis was placed on obtaining a comparative bond behavior under static and dynamic loads.

CHAPTER 2

TEST SPECIMENS

2.1 DESCRIPTION OF TEST SPECIMEN

The test specimen essentially consisted of a reinforced concrete block as shown in Fig. 2.1, into which bond bars were embedded. In all, twenty two specimens were tested. These specimens are subgrouped as follows:

Type I. These are the specimens with 2 #8 bars, having a bond length of 3" and a concrete strength of 3500 psi. Four specimens were tested in this type.

Type II. These are similar to Type I except for the concrete strength of 2000 psi. Four specimens were tested in this type.

Type III. These are also similar to Type I except for the Concrete strength of 6000 psi. Five specimens were tested in this type.

Type IV. This consists of specimens with 2 #14 bars, having a bond length of $5\frac{1}{16}$" and a concrete strength of 3500 psi. Six specimens were tested in this type.

Type V. This consists of specimens with 2 #10 bars, having a bond length of $3\frac{13}{16}$" and a concrete strength of 3500 psi. Three specimens were tested in this type.

The general appearance of the specimens is shown in Fig. 2.1. The concrete block was nominally reinforced as shown in Fig. 2.2. The details of bond bars and their preparation are shown in Fig. 2.3.

As shown in Fig. 2.1, the bond bars extend throughout the length of the concrete block. However, only the portion of bar marked "bond length" is in contact with concrete, while the rest of the bar is prevented from coming into contact with concrete by cast iron pipe sleeves with rubber stoppers at their ends. This permitted the placing of the effective bond length of bars far inside the specimen, where there was adequate reinforcing to prevent splitting and cracking. The extension of bond bars beyond the rear end of concrete block permitted the measurements of slip at the unloaded end of the bar.

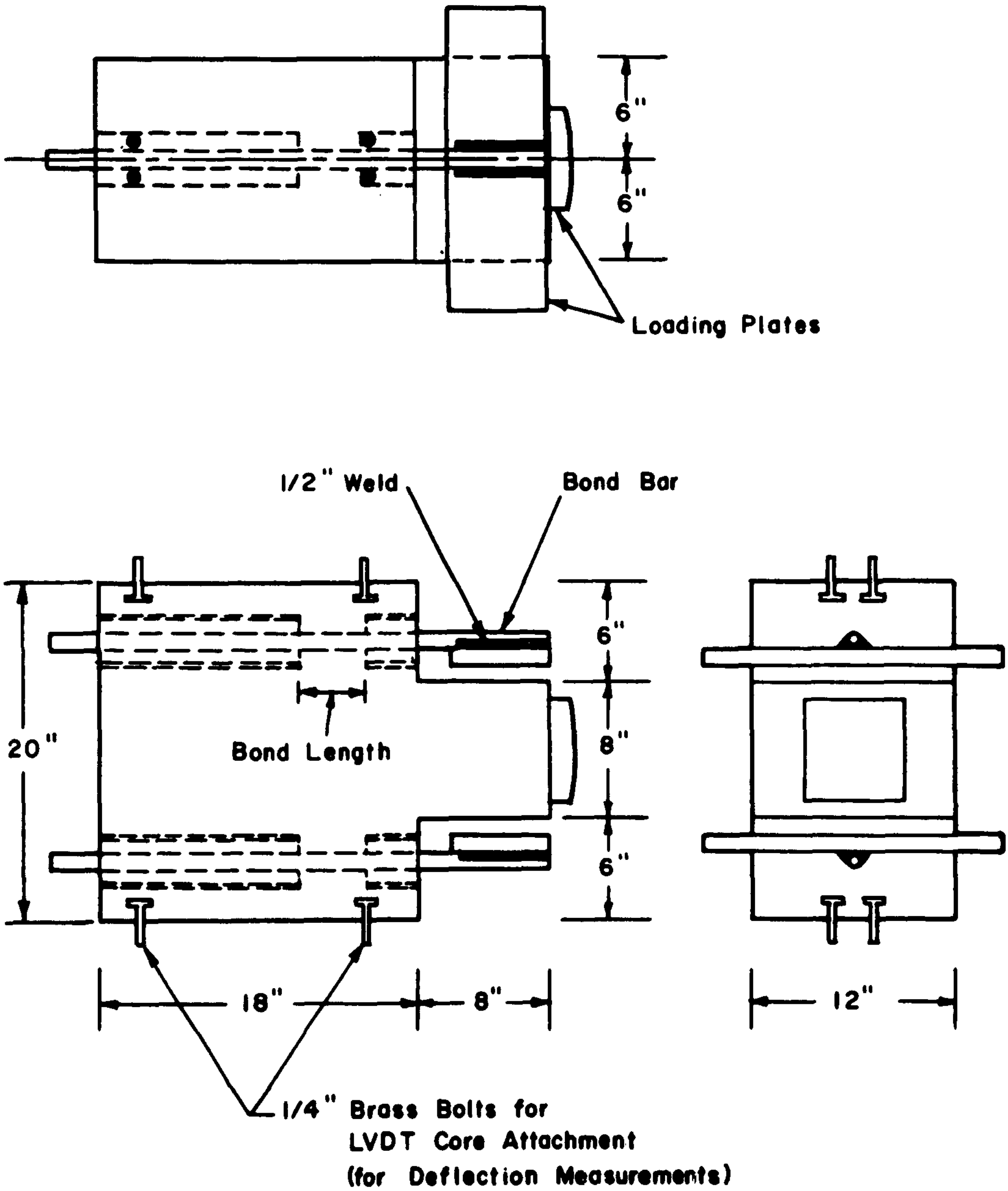


FIGURE 2.1 - APPEARENCE OF TEST SPECIMEN

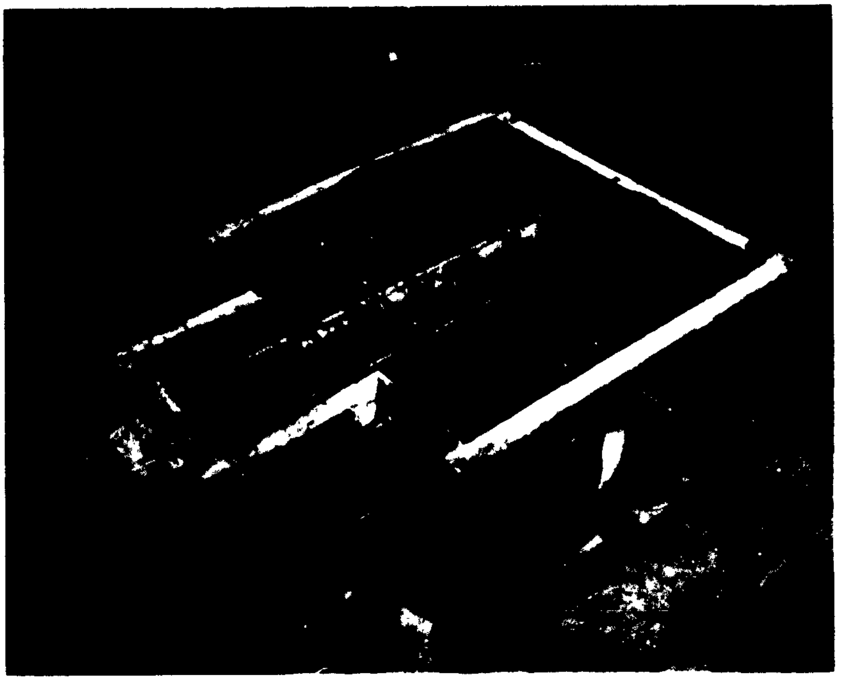


FIGURE 2.2 - REINFORCEMENT OF TEST SPECIMEN

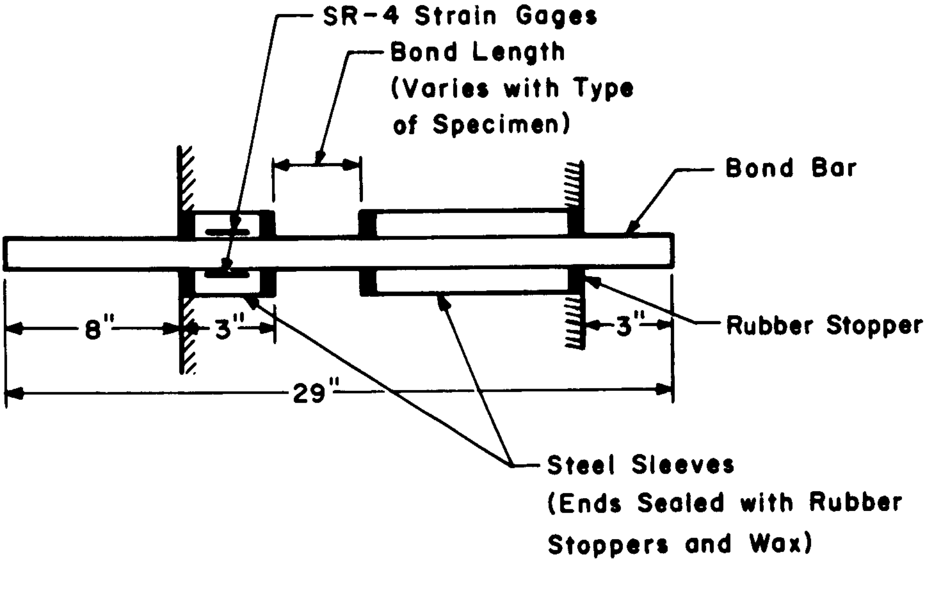


FIGURE 2.3-DETAILS OF BOND BAR

As shown in Fig. 2.3, two strain gages were mounted on each bond bar of the specimen. This permitted the measurements of strain and the load carried by each bar.

It should be noted that in each of the above specimens the ratio of bond length to diameter of bond bar is three. This ratio was chosen in order to induce a bond failure, rather than the failure of specimen by the fracture of bond bar.

The further details of each of the above specimens are given in Table 2.1.

2.2 MATERIAL PROPERTIES

The concrete mixes were designed for 2000 psi, 3500 psi and 6000 psi concrete. The proportions of the mixes are as follows:

(a) For 2000 psi concrete

1 part by weight, high early strength cement,
4.86 parts by weight of sand,
5.96 parts by weight of coarse aggregate,
11.3 gallons of water per sack of cement.

(b) For 3500 psi concrete

1 part by weight, high early strength cement,
2.64 part by weight of sand,
3.60 part by weight of coarse aggregate,
7.75 gallons of water per sack of cement

(c) For 6000 psi concrete

1 part by weight of high early strength cement,
0.59 part by weight of sand,
1.37 part by weight of coarse aggregate,
3.88 gallons of water per sack of cement.

The sand used had a fineness modulus of 2.2 and the maximum size of coarse aggregate was 3/4".

The steel bars used as nominal reinforcement of the block were intermediate grade #3 and #2 bars. The bond bars #8 and #10 were of standard deformation, conforming to ASTM specification A 305-56T,

TABLE 2.1*

GENERAL DATA OF SPECIMENS

Specimen No.*	Type	Diameter of Bond Bar (inches)	Total Bond Length (inches)	Actual f_c' (psi)	Static Steel Strength (ksi)	
					Yield	Ultimate
1	I	1	6	3380	42	76.5
2	I	1	6	3640	42	76.5
3	I	1	6	3240	42	76.5
4	I	1	6	3700	42	76.5
5	II	1	6	1960	42	76.5
6	II	1	6	1730	42	76.5
7	II	1	6	1800	42	76.5
8	II	1	6	2180	42	76.5
9	IV	1.69	10.14	3810	72.3	109.7
10	IV	1.69	10.14	3720	72.3	109.7
11	IV	1.69	10.14	3640	72.3	109.7
14	IV	1.69	10.14	3330	72.3	109.7
17	IV	1.69	10.14	3260	72.3	109.7
18	IV	1.69	10.14	3050	72.3	109.7
12	III	1	6	6350	42	76.5
13	III	1	6	6100	42	76.5
15	III	1	6	5900	42	76.5
16	III	1	6	5300	42	76.5
22	III	1	6	4600	42	76.5
19	V	1.27	7.62	3420	41	76.4
20	V	1.27	7.62	3600	41	76.4
21	V	1.27	7.62	2540	41	76.4

* Specimens are presented as in groups and not in chronological order.

while the bond bars #14 were also of standard deformation, conforming to ASTM specification A 408-58T. The static yield and ultimate strengths of these bond bars are given in Table 2.1.

2.3 PREPARATION OF SPECIMENS

2.3.1 Bond Bars. The bond bars were 29" long. The deformations of the bars were removed in about 2" length at the places where the gages were to be mounted (Fig. 2.3). On this clean and smooth surface, two SR-4 strain gages were mounted diametrically opposite and along the axis of the bar, using duco cement and allowed to dry for 24 hours. When dry, gages were connected in series and lead wires were attached. Waterproofing of gages consisted in covering the gages with scotch plastic tape and a coat of wax. The cast iron sleeves as shown in Fig. 2.3 were then mounted on the bar and the ends of the sleeves were sealed by the rubber stoppers and a coat of wax. The cast iron sleeves thus protected the strain gages as well as prevented bonding of concrete to the bond bar, except the portion of the bond bar marked "Bond Length" in Fig. 2.3.

2.3.2 Casting and Curing of Concrete. The formwork consisted of 1/8" thick steel plates suitably connected together by angles and bolts as shown in Fig. 2.2. The base plate of the form work was 1/4" thick. The reinforcement cage, as shown in Fig. 2.2, was placed in the formwork. The bond bars were then inserted through the holes in the formwork and the sleeves were tack welded with the formwork so that the bars would not change their position while the concrete was being poured in the formwork. When in place, bond bars appeared horizontally and their horizontal position was maintained during casting. Though it is known that vertical orientation of bars gives better bond, vertical casting of specimen was considered impractical due to the shape of the specimen. The bolts and other fixtures necessary for mounting the lifting devices and the linear variable transformers, etc., were inserted in the formwork before casting each specimen.

Concrete was mixed in a tilting drum type mixer of 9 cubic feet capacity. With each specimen three 6" x 12" control cylinders were also cast. Specimens were allowed to set for about 24 hours after which the formwork was stripped. The specimen and control cylinders were cured in the air of laboratory until tested.

2.3.3 General. Before mounting the specimen in the loading machine, the bond bars, as shown in Fig. 2.2, were welded to the steel plates which transferred the load from the bond bars to the supporting frame. After the specimen was in place in the loading machine, the linear variable differential transformers (called LVDT hereafter in the report) were attached to the specimen and connected to the recording equipments. The strain gages were also connected to the recording equipments.

CHAPTER 3

EQUIPMENT AND INSTRUMENTATION

3.1 LOADING MACHINE

For the purpose of these tests, the large capacity dynamic loading machine, designed and constructed under Contract DA-49-129-Eng -325 with the Department of the Army, was used. This machine[10] was designed to develop a load of 300 kips in 10 milliseconds. It is capable of producing a variety of different pulses with rise time not less than 10 milliseconds. The machine is also adaptable for static tests.

The dynamic load pulse used in this test program was roughly of a triangular shape, with a rise time between 15 to 30 milliseconds.

The support arrangement of the specimen is shown in Fig. 3.1. Essentially it consisted of a supporting frame which holds the specimen and which in turn is supported by a U-frame of the loading machine. The load is transferred from the specimen to the supporting frame, which transfers the load to the truss of the loading machine via a strut.

3.2 MEASURING EQUIPMENT

In order to study the behavior of test specimens it was necessary to measure the following quantities.

(1) Applied load

(2) Reaction

(3) Relative displacement between concrete block and bond bars

(4) Acceleration of the test specimen.

These quantities were measured as follows:

3.2.1 Applied Load. The load was measured by a bridge of eight C-7 strain gages (500 ohms) mounted on the loading ram. The signal from this strain gage bridge was fed into a DuMont Dual Beam Cathode Ray Oscilloscope Type 333 and also into an eighteen channel recording oscillograph, Type 5-114-P3, manufactured by the Consolidated Electrodynamics Company. (Hereafter in this report, this equipment will be referred to as C.E.C. Recorder.) In dynamic tests the permanent record

FIGURE 3.1 - SUPPORT ARRANGEMENT FOR TEST SPECIMEN

of the trace from the screen of the oscilloscope was obtained on the polaroid film by using DuMont oscilloscope record camera Type 247. In static tests, the trace from the screen of the oscilloscope was recorded directly by an observer. The traces of the galvanometers of the C.E.C. recorder were recorded on the photographic paper in both dynamic and static tests. Thus the applied load was measured by two separate instruments.

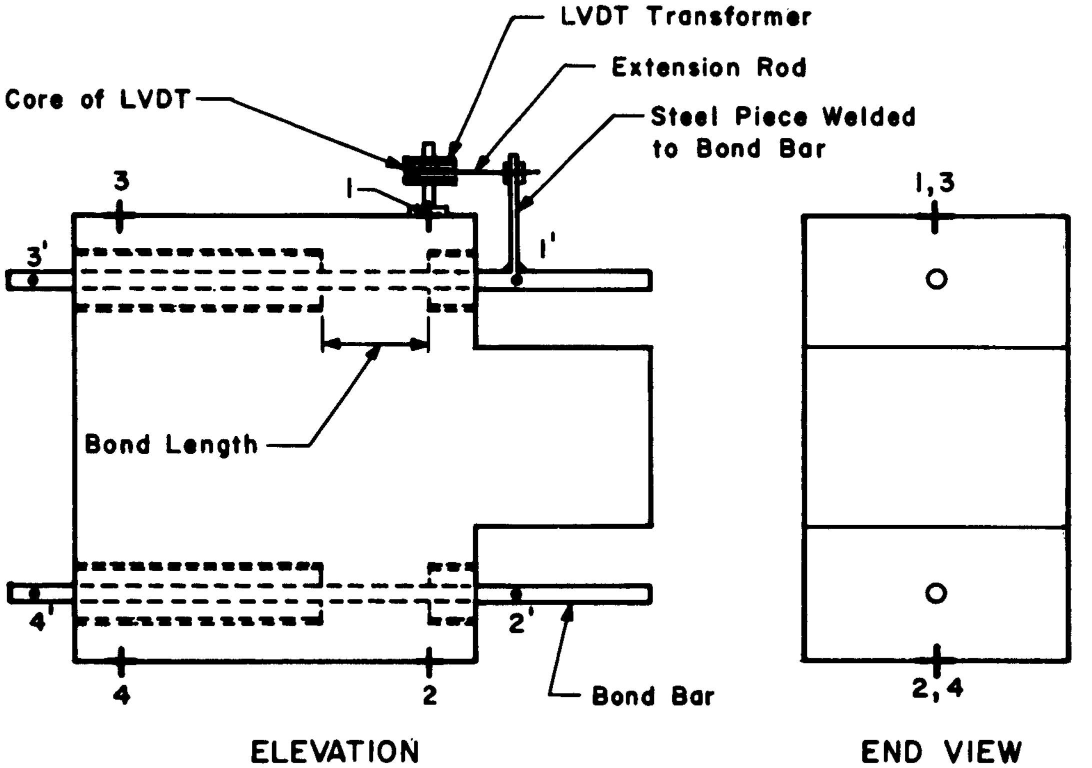
3.2.2 Reaction. The reaction, at the other end of the supporting frame was measured by a 300 kips capacity load cell. This load cell was a fabricated aluminum I-section, on the web of which were mounted SR-4 C-7 strain gages (500 ohms). The output of the load cell was measured by the C.E.C. Recorder.

3.2.3 Relative Displacement Between Concrete Block and Bond Bars.

In order to measure the slip at the loaded and unloaded end of the bond length, electric inductance gages of moving core solonoid type, commonly known as Linear Variable Differential Transformer (LVDT) were used. These gages were of Type 020 MS-L with a linear range of $\pm$ 0.020". The transformers of these LVDT's were mounted on the concrete block at four points as shown in Fig. 3.2. Thin steel pieces were welded to the bond bars at four points, as also shown in Fig. 3.2. The moving cores of the LVDT's were connected to these steel pieces through a suitable extension rod.

The output of the transformer due to the movement of the core was amplified by a suitable amplifier system (Type 1-113C, 3KC carrier amplifiers manufactured by Consolidated Electrodynamics Corporation) This amplified signal was then fed into the C.E.C. recorder and continuous traces were obtained on photographic paper.

It is clear that the displacement measured by the LVDT's at the points 1 and 2 (Fig. 3.2) includes the elongation of the bond bars, between the loaded end of the bond length and the points 1' and 2' (Fig. 3.2) on bond bars where the cores of the LVDT's are connected. To measure this elongation of the bond bar, two SR-4 C-7 strain gages (500 ohms) were mounted on each bond bar as shown in Fig. 2.3. Net slip at the loaded end is then equal to the displacement measured by the



Note: LVDT Transformers are Mounted at Points 2, 3 and 4 in the Same Way as Shown at Point 1. Cores of the LVDT'S are Connected to Points 2', 3' and 4' in the Same Way as Shown at Point 1'.

FIGURE 3.2-LOCATION OF DEFLECTION MEASUREMENTS

LVDT's minus the elongation measured by the strain gages. The strain gages were also useful in determining the load carried by each of the two bond bars in the test specimen. The output of these strain gages, both in static and dynamic tests was recorded by the C.E.C. Recorder.

3.2.4 Acceleration of Test Specimen. In order to determine the magnitude of the inertial forces on the test specimens, the acceleration of the test block was measured by Statham Accelerometer (Model C-40-180, range $\pm$ 40 g). The output of the accelerometer was measured by Strain Gage Amplifier (Model 64-500B), coupled with "Twin Viso" Recorder (Model 60-1300), manufactured by Sanborn Company.

CHAPTER 4

TESTS

4.1 TESTING PROCEDURE

The main aim of this research program was to study the comparative bond behavior of reinforcing bars under static and dynamic loading, as influenced by various parameters, such as compressive strength of concrete and diameter of the reinforcing bars. To achieve this objective, the testing procedure adopted was as follows.

In static tests the load to the specimen was applied in suitable equal increments. Each increment consisted of about 5 kips of load. This was done by building the required oil pressure in equal steps on the push side of the jack of the loading machine. After each increment the load was held steady for about 30 seconds and the measurements of the load and deflections were recorded on the C.E.C. recorder. The loading was continued in this way until the specimen failed. The total duration of the test was about ten minutes.

In dynamic tests a triangular shape load pulse was applied in such a way that the specimen failed on the rising part of the pulse. This was done by appropriately programming the loading machine so that it would apply a dynamic pulse to the specimen, slightly greater in magnitude than the estimated resistance of the specimen at failure. The rise time of the failure load was between 10 to 20 milliseconds and the decay time varied between 30 and 70 milliseconds. The reason for applying only one pulse to the specimen was to avoid any permanent damage which might be caused to the specimen before failure, due to repetitive pulses. A continuous record of the deflections and load was obtained as described in Chapter 3.

In both static and dynamic tests, a small static load of the order of 3 to 4 kips was initially applied and removed to check all the equipment.

4.2 GENERAL

Twenty two specimens tested in this program are grouped into five types as described in Section 2.1 (Chapter 2). The results within each group are presented in the order of the bond strength at failure, rather than in a chronological order.

4.3 TESTS OF TYPE I SPECIMENS

The test results for these specimens are given in Table 4.1.

4.3.1 Static Tests - Specimen No. 4. The failure load for specimen #4 was 43 kips. The failure was by complete pull-out of both the bars, with a small amount of splitting of concrete. One of the two bars carried about 20% more load than the other. This could be due to the poorer bond on one bar than on the other.

In Figure 4.1 are given the plots of average bond stress vs. slip at the unloaded end (i.e., gage points 3 and 4 - Fig. 3.2) of the bond length for this specimen.

4.3.2 Dynamic Tests - Specimen Nos. 1, 2, and 3. Failure loads for specimens #1, 2, and 3 were 57, 50.5 and 46 kips. The failure of specimen #1 was by complete pull-out of both bars, with a small amount of splitting near one of the two bars while specimens #2 and 3 failed by complete pull-out of both the bars without any splitting of the concrete. In specimen #1, one of the two bars yielded at the gage point, while in specimens 2 and 3, none of the bars yielded. In specimen #1, the yielding of the bottom bond bar seems to be due to the fact that the applied load was eccentric by 1/4" towards the bottom bar and therefore this bar carried a larger share of the applied load than the top bond bar. After the bottom bar yielded, top bond bar carried the additional applied load and finally both the bars were pulled out.

In Figure 4.2 are shown the plots of average bond stress vs. time, and slip at the loaded end (i.e., gage points 1 and 2 - Fig. 3.2) and at the unloaded end (i.e., gage points 3 and 4 - Fig. 3.2) of the bond length vs. time, for specimen #2.

4.3.3 Discussion. Table 4.1 indicates that the average ultimate bond stress "u" is 0.62 f_c' for static tests, while it is about 0.79 f_c' for the dynamic tests. Thus there is a percent increase of 27% in the dynamic tests.

4.4 TESTS OF TYPE II SPECIMENS

The test results of Type II specimens are shown in Table 4.2.

4.4.1 Static Tests - Specimen No. 8. The failure load of this specimen was 23.5 kips. The failure was by complete pull out without any splitting. The top bond bar carried about 20% larger load than bottom

TABLE 4.1

SUMMARY OF TYPE I SPECIMENS

Specimen No.	Type of Test	f'_c (psi)	Failure Load (kips)	Rise Time of Failure Load (ms.)	Average Bond Stress at Failure - u (psi)	u/f'_c
4	Static	3700	43	-	2280	0.62
1	Dynamic	3380	57	18	3020	0.89
2	Dynamic	3640	50.5	15	2680	0.74
3	Dynamic	3240	46	16	2440	0.75

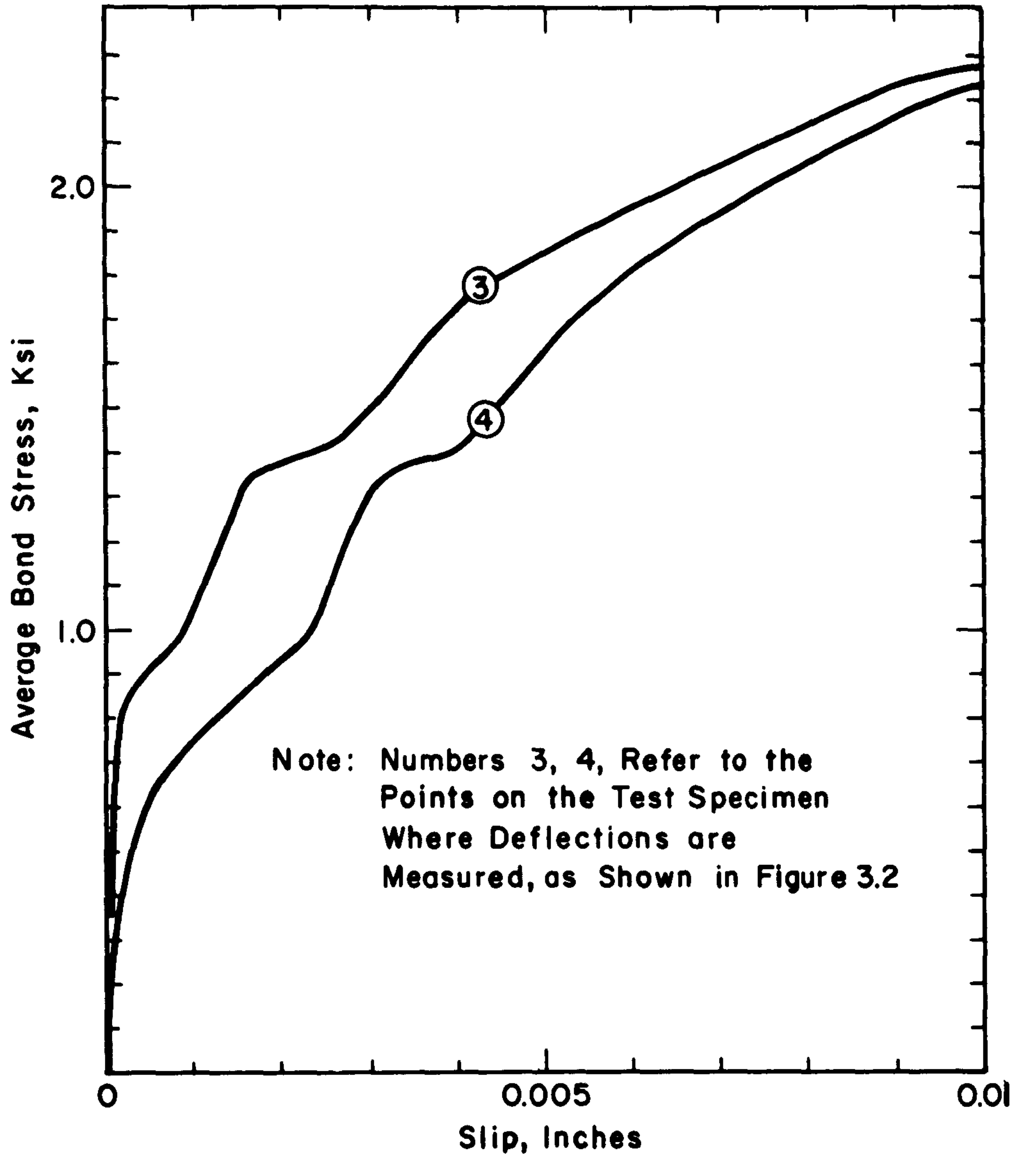


FIGURE 4.1 -PLOT OF BOND STRESS VS. SLIP (SPECIMEN NO. 4 - STATIC TEST)

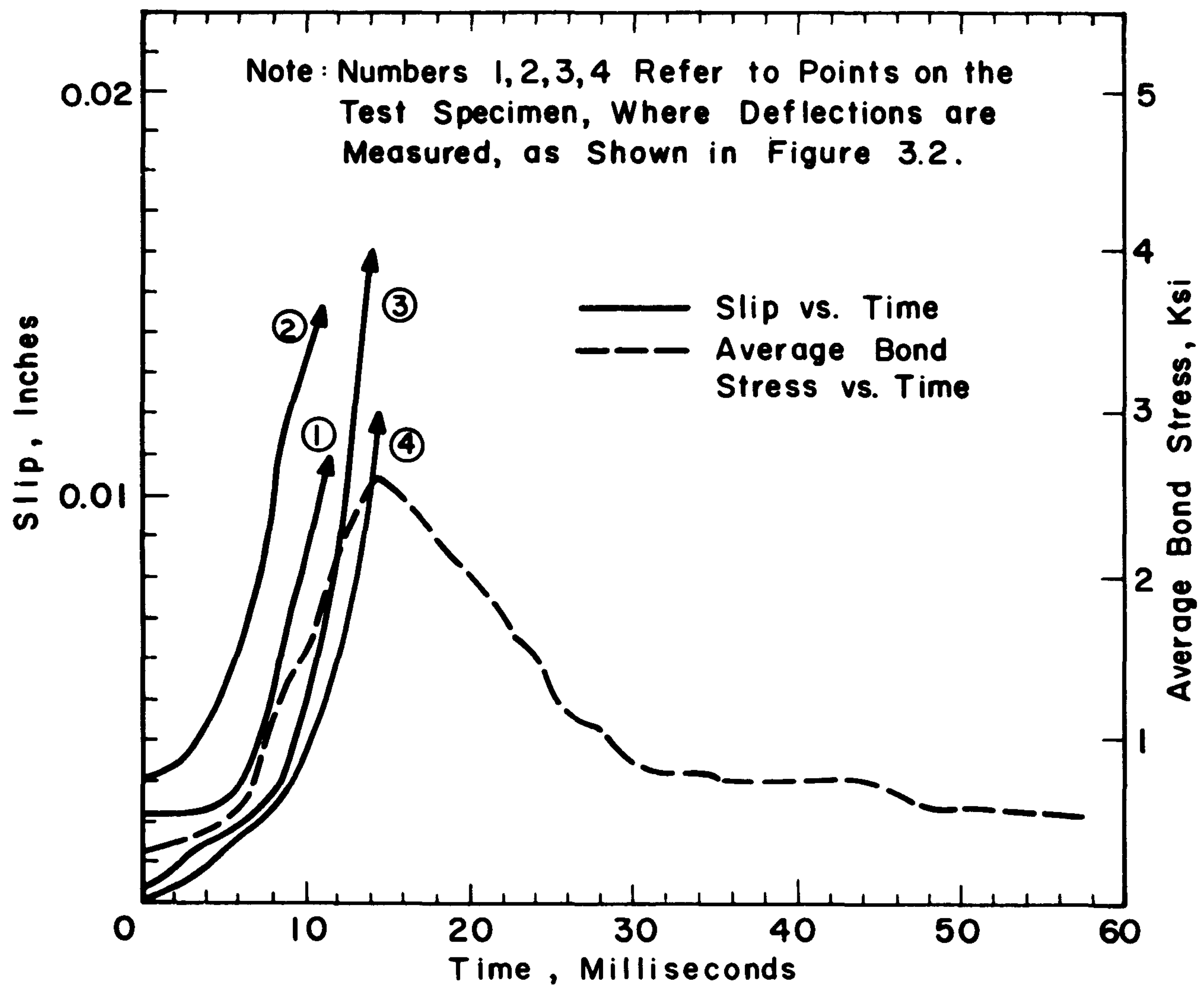


FIGURE 4.2—SPECIMEN NO. 2—DYNAMIC TEST

TABLE 4.2

SUMMARY OF TYPE II SPECIMENS

Specimen No.	Type of Test	f'_c (psi)	Failure Load (kips)	Rise Time of Failure Load (ms.)	Average Bond Stress at Failure - u (psi)	u/f'_c
8	Static	2180	23.5	-	1250	0.58
6	Dynamic	1730	34	15	1805	1.04
5	Dynamic	1960	31.5	10	1670	0.85
7	Dynamic	1800	30	11	1595	0.89

bar. This could probably be due to poorer bond on the bottom bar. The data on the slip measurements at loaded and unloaded ends of the bond length was not obtained due to the malfunctioning of the measuring equipment.

4.4.2 Dynamic Tests - Specimen Nos. 6, 5 and 7. The failure loads for specimens #6, #5 and #7 were 34, 31.5 and 30 kips respectively. All three specimens failed by complete pull out without any splitting. In specimen #5 load carried by top bar was 16% larger than bottom bar, while for specimen #7 it was about 20% larger. In specimen #6 strain gages mounted on the top bar were damaged before the test and therefore the direct results of the load carried by the top bar and the elongation of the top bar were not obtained.

In Figure 4.3 are shown the plots of average bond stress vs. time and slip at the unloaded end of the bond length vs. time, for specimen #7.

4.4.3 Discussion. Table 4.2 indicates that average failure bond stress "u" for the static test is about 0.58 f_c' while "u" is about 0.92 f_c' for dynamic tests. Thus there is an increase in "u" by about 58% in dynamic tests.

Table 4.2 also indicates that the f_c' of specimens #6, #5 and #7 were very close and that the failure loads of each of these specimens were also in very good agreement.

4.5 TESTS OF TYPE III SPECIMENS

The test results of this type specimen are shown in Table 4.3.

4.5.1 Static Tests. - Specimen Nos. 22 and 16. The failure loads for specimens #22 and #16 were 50 and 46.5 kips, respectively. In specimen #16 the failure was by complete pull-out with splitting of concrete, while in specimen #22 the specimen failed by the pulling out of only the bottom bond bar. This happened probably due to the poorer bond on the bottom bar, because the strain gages on both the top and bottom bar indicated that the bars were carrying equal loads until failure, when only the bottom bar was suddenly pulled out. No splitting of concrete was observed near the bottom bar. A slightly lower failure load of specimen #16 could be due to the fact that pull-out failure

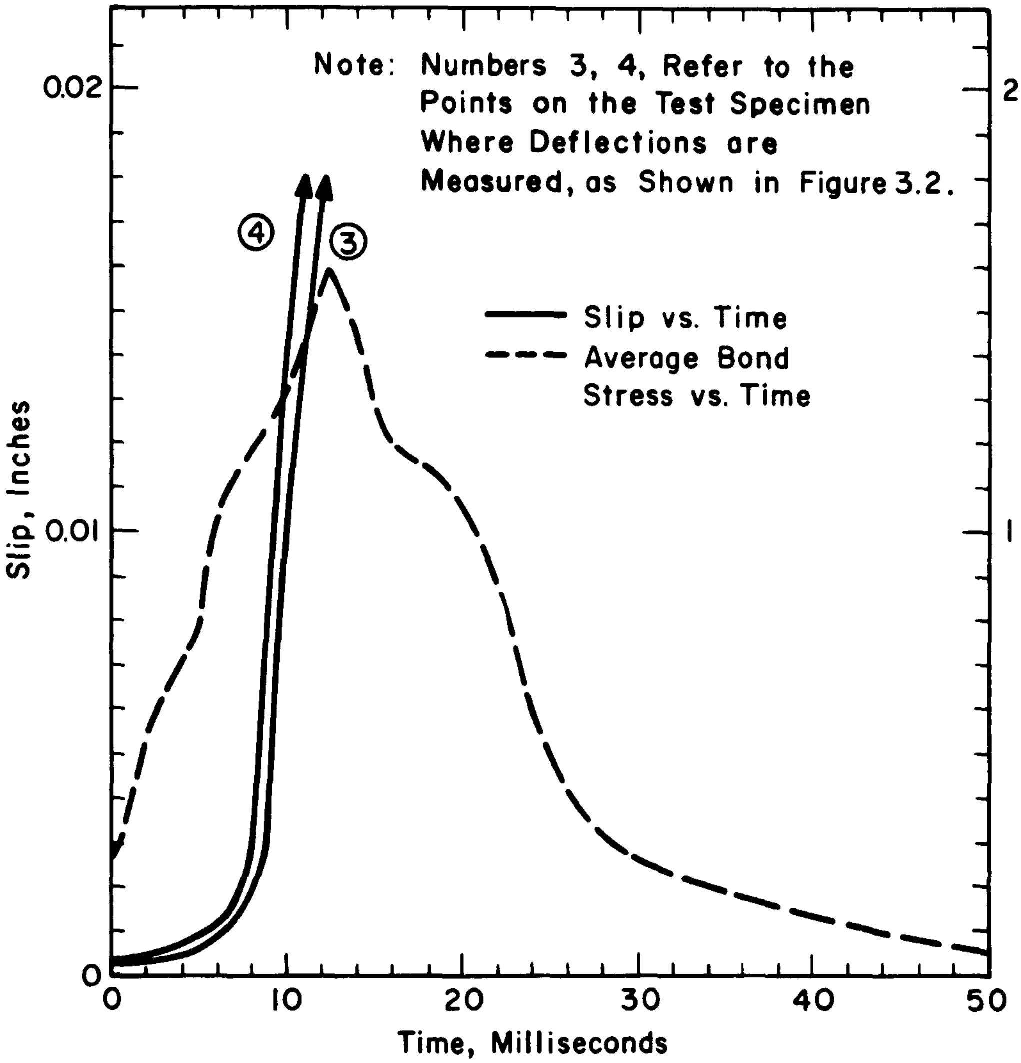


FIGURE 4.3- SPECIMEN NO. 7-DYNAMIC TEST

TABLE 4.3

SUMMARY OF TYPE III SPECIMENS

Specimen No.	Type of Test	f'_c (psi)	Failure Load (kips)	Rise Time of Failure Load (ms.)	Average Bond Stress at Failure - u (psi)	u/f'_c
22	Static	4600	50	-	2650	0.58
16	Static	5300	46.5	-	2460	0.48
12	Dynamic	6350	85	14	4500	0.71
13	Dynamic	6100	80	13	4250	0.70
15	Dynamic	5900	70	11	3700	0.63

was accompanied by splitting.

The plots of average bond stress vs. slip at the unloaded end of the bond length, for specimen #16, are shown in Figure 4.4.

4.5.2 Dynamic Tests - Specimen Nos. 12, 13 and 15. The failure loads of specimens #12, #13, and #15 were 85, 80 and 70 kips. Specimen Nos. 12, and 13 failed by complete pull-out with a very slight amount of splitting, while specimen #15 failed also by pull-out but with a considerable amount of splitting. This could account for its lower failure load compared to specimens #12 and #13. In all the three specimens the bond bars also yielded at the gage points.

4.5.3 Discussion. Table 4.1 indicates that average ultimate bond stress "u" for static test is about 0.53 f'_c , while for dynamic tests "u" is about 0.68 f'_c . Thus there is a percentage increase of about 28% in dynamic tests.

4.6 TESTS OF TYPE IV SPECIMENS

The test results of these specimens are given in Table 4.4.

4.6.1 Static Tests - Specimen No. 18. The failure load of specimen #18 was 82.5 kips. The failure was by complete pull-out of bars with a fair amount of splitting of concrete. The strain gages on the bottom rod were damaged before the test and as a result no direct data on the load carried by the bottom bar was obtained. However, the strain gages on the top bar indicated that each bar was carrying half of the total load.

The plots of average bond stress vs. slip at the unloaded end of the bond length, for this specimen, are given in Fig. 4.5.

4.6.2 Dynamic Tests - Specimen Nos. 14, 11 and 17. The failure loads of specimens #14 and #11 were 114 and 110 kips. Both specimens failed by complete pull-out of bond bars with fair amount of splitting. For specimen #11 the top bond bar carried about 20% more load than the bottom bar, while for specimen #14 both the bars carried almost equal loads. The lower failure load (91 kips) of specimen #17 seemed to be due to the fact that the specimen failed by the pulling out of bottom bar only. This could have happened because of the poorer bond on the

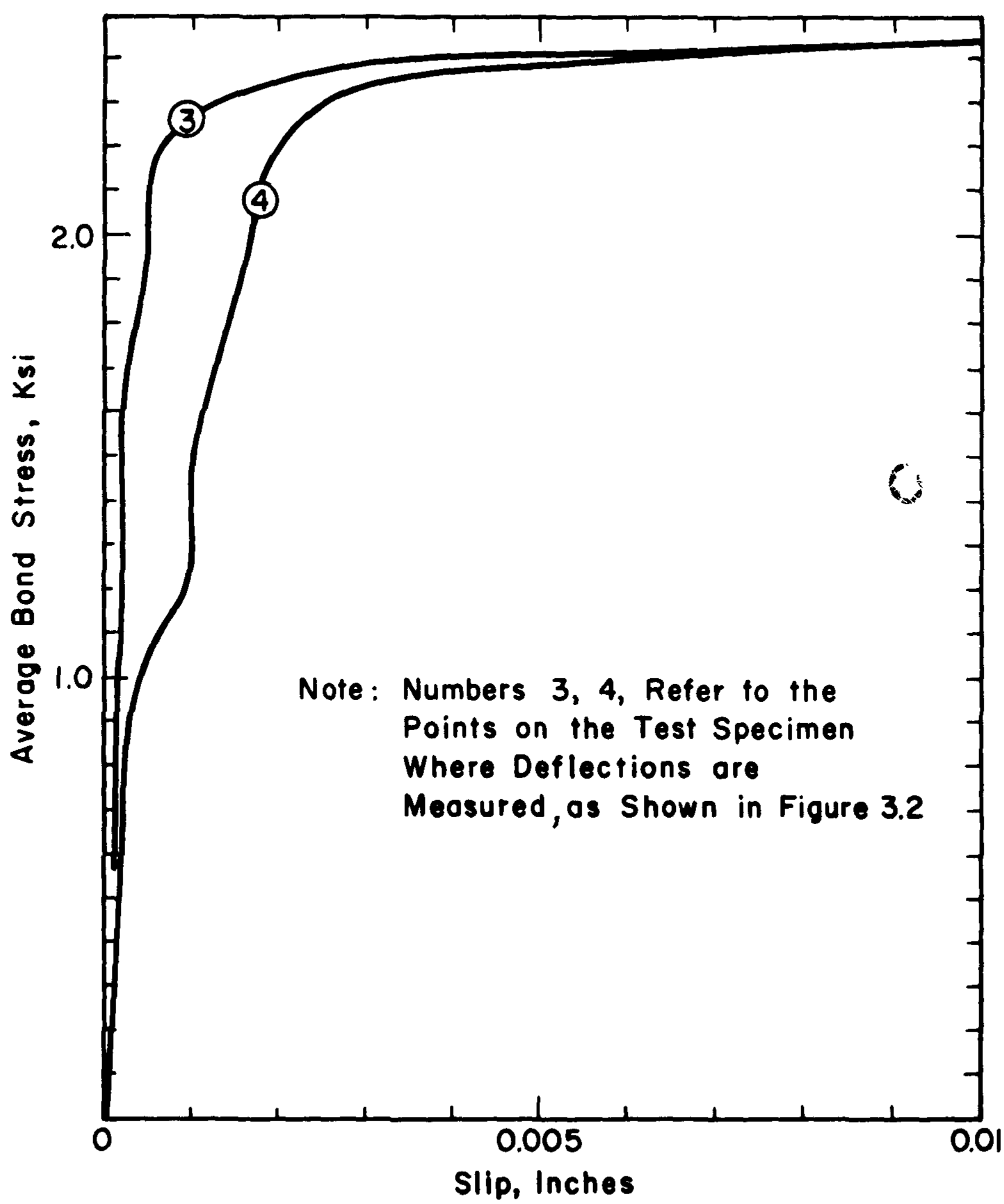


FIGURE 4.4 - PLOT OF BOND STRESS VS. SLIP (SPECIMEN NO. 16 - STATIC TEST)

TABLE 4.4

SUMMARY OF TYPE IV SPECIMENS

Specimen No.	Type of Test	f'_c (psi)	Failure Load (kips)	Rise Time of Failure Load (ms.)	Average Bond Stress at Failure - u (psi)	u/f'_c
18	Static	3050	82.5	-	1530	0.50
14	Dynamic	3330	114	19	2100	0.63
11	Dynamic	3640	110	17	2040	0.56
17	Dynamic	3260	91	15	1690	0.52

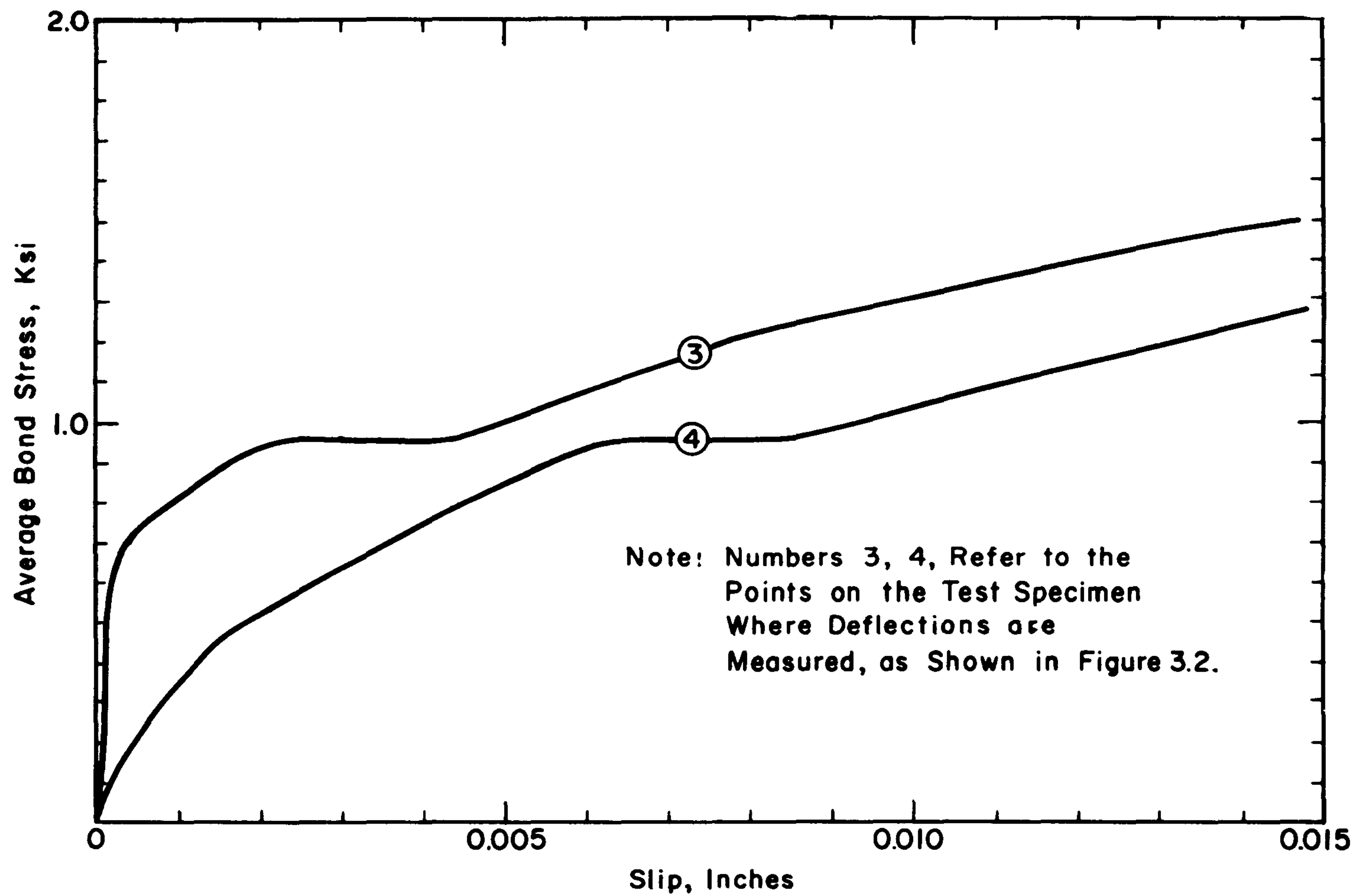


FIGURE 4.5-PLOT OF BOND STRESS VS. SLIP (SPECIMEN NO. 18-STATIC TEST)

bottom bar than on the top bar. A fair amount of splitting of concrete was also observed near the bottom bar.

The test results of specimens 9 and 10 are not reported because no reliable results were obtained due to malfunctioning of either loading machine or the measuring equipment.

In Figure 4.6 are shown the plots of average bond stress vs. time and slip at the unloaded end of the bond length vs. time, for specimen #17.

4.6.3 Discussion. For this category, Table 4.4 indicates that the static ultimate bond stress "u" is 0.50 f_c', while the average dynamic ultimate bond stress is about 0.57 f_c'. Thus there is an increase of 14% in the dynamic tests.

4.7 TESTS OF TYPE V SPECIMENS

The test results of these specimens are summarized in Table 4.5.

4.7.1 Static Tests - Specimen No. 21. The failure load of this specimen was 45 kips. The failure was by complete pull-out of bars with a small amount of splitting. The data from the strain gages on both the bars indicated that each bar was carrying half of the applied load. No reliable data on the slip measurements was obtained for this specimen, due to malfunctioning of the LVDT's.

4.7.2 Dynamic Tests Specimen Nos. 19 and 20. The failure loads of specimen #19 and #20 were 80 and 68 kips respectively. Both the specimens failed by complete pull-out of the bars. The data from the strain gages on the bars indicated that bars in both the specimens yielded at the gage points.

The plots of average bond stress vs. time and slip at the unloaded end of the bond length vs. time, for specimen #20, are given in Figure 4.7.

4.7.3 Discussion. Table 4.4 shows that the static ultimate bond stress "u" is 0.58 f_c', while the average dynamic bond stress is 0.70 f_c'. Therefore, the increase in the bond strength in dynamic tests is of the order of 21%.

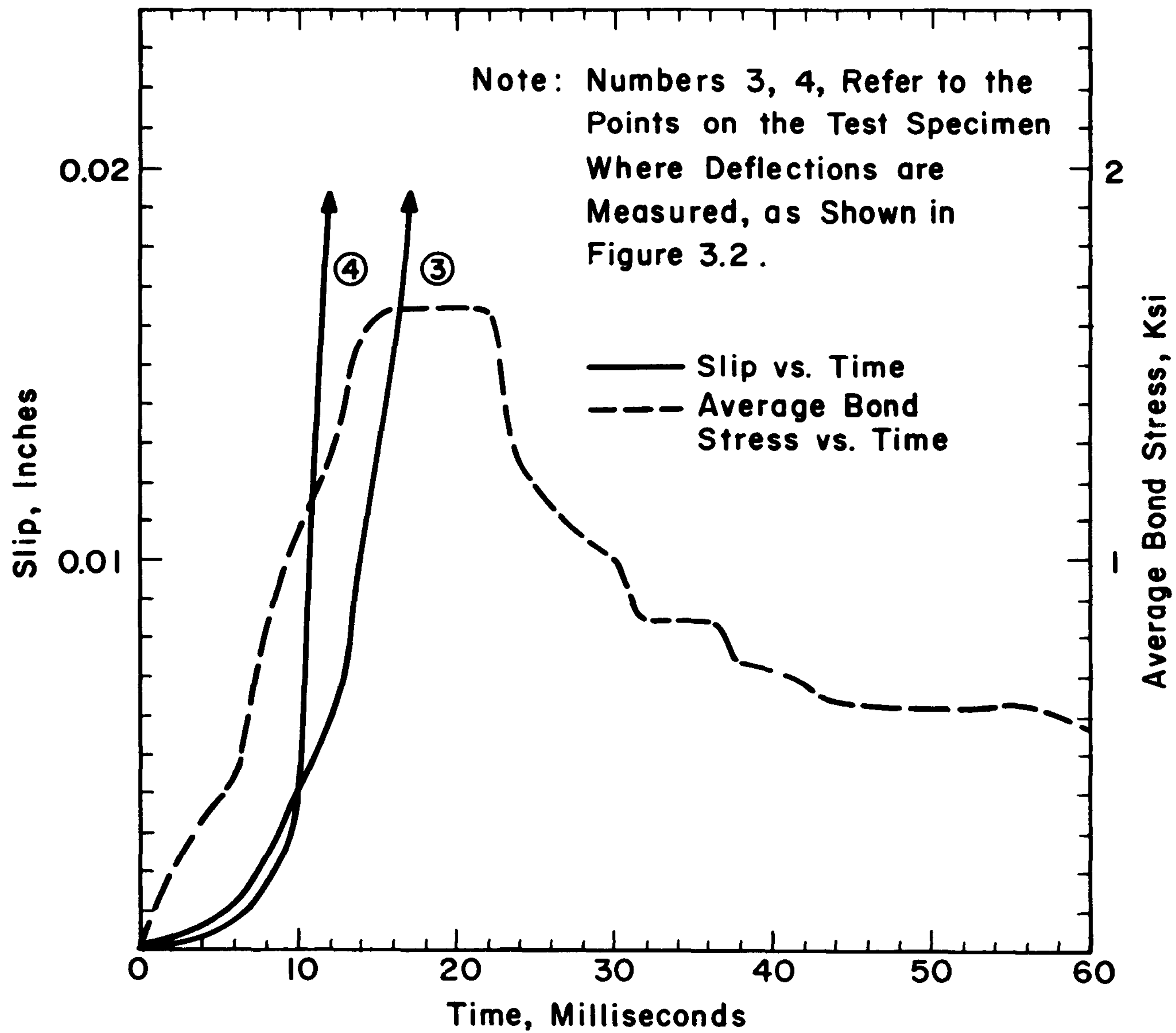


FIGURE 4.6 - SPECIMEN NO. 17-DYNAMIC TEST

TABLE 4.5

SUMMARY OF TYPE V SPECIMENS

Specimen No.	Type of Test	f'_c (psi)	Failure Load (kips)	Rise Time of Failure Load (ms.)	Average Bond Stress at Failure - u (psi)	u/f'_c
21	Static	2540	45	-	1480	0.58
19	Dynamic	3420	80	17	2630	0.77
20	Dynamic	3600	68	13	2240	0.63

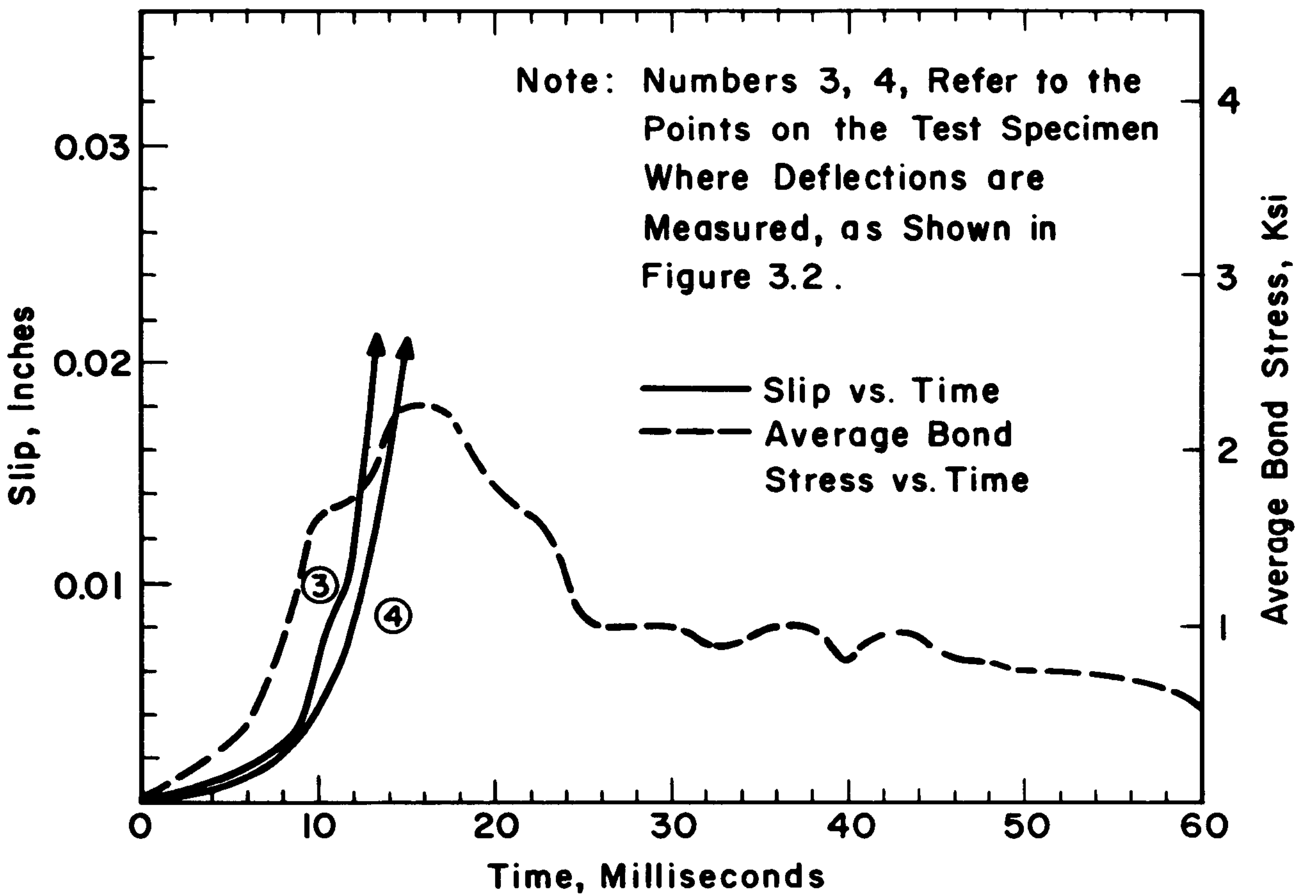


FIGURE 4.7-SPECIMEN NO. 20-DYNAMIC TEST

CHAPTER 5

GENERAL DISCUSSION

The main purpose of this research program was to study the influence of the concrete compressive strength f'_c and the diameter of the bond bars on the static and dynamic bond strength of concrete. In order to understand the influence of these parameters, the average values of the ultimate bond stress "u" and the average values of u/f'_c for each category of tests (section 2.1) are given in Tables 5.1 and 5.2. Table 5.1 summarizes the test results of those specimens in which f'_c is a variable parameter, while in Table 5.2 the test results are summarized for those specimens in which the diameter of the bond bar is a variable parameter. In Tables 5.1 and 5.2, a comparison between the static and dynamic bond behavior of each category is also made in terms of "u" and u/f'_c ; and a percentage increase in "u" and u/f'_c under dynamic loading is given.

Table 5.1 clearly indicates that both in the static and dynamic case, the ultimate bond, stress "u" increases with the increase in the compressive strength of concrete. In the static case, the increase in "u" seems more or less directly proportional to f'_c, as the ratio of u/f'_c varies only between 0.53 and 0.62. In the dynamic case however, this is not so. The u/f'_c ratio varies from 0.92 to 0.68 as the compressive strength of concrete varies from 2000 psi to 6000 psi. This suggests that the influence of strain rate on the bond strength varies with different concrete compressive strengths. Table 5.1 also shows that the percentage dynamic increase in u/f'_c is more for lower strength concrete than for moderate or higher strength concrete.

Table 5.2 shows that both in the static and dynamic case the average u/f'_c ratio decreases with the increase in the diameter of bond bars. The ratio u/f'_c varies from 0.62 to 0.50 in the static case as the diameter of bond bar varies from 1" to 1.69". The corresponding variation in the dynamic case is from 0.79 to 0.57. It is also seen from Table 5.2 that percentage dynamic increase in u/f'_c ratio varies inversely with the diameter of the bond bar.

TABLE 5.1

COMPARISON OF STATIC AND DYNAMIC BOND STRESS AND u/f'_c FOR VARIOUS VALUES OF f'_c

Specimen Type	Characteristic Feature	Type of Failure	Static		Dynamic		Percentage Increase	
			u psi	u/f'_c	u psi	u/f'_c	u	u/f'_c
II	2 #8 Bars, Bond Length = 3", f'_c = 2000 psi	Pull-out	1250	0.58	1690	0.92	35%	58%
I	2 #8 Bars, Bond Length = 3", f'_c = 3500 psi	Pull-out	2280	0.62	2710	0.79	19%	27%
III	2 #8 Bars, Bond Length = 3", f'_c = 6000 psi	Pull-out with Splitting	2555	0.53	4150	0.68		28%

TABLE 5.2

COMPARISON OF STATIC AND DYNAMIC BOND STRESS AND u/f'_c FOR VARIOUS BOND BAR DIAMETERS

Specimen Type	Characteristic Feature	Type of Failure	Static		Dynamic		Percentage Increase	
			u psi	u/f'_c	u psi	u/f'_c	u	u/f'_c
I	2 #8 Bars, Bond Length = 3", f'_c = 3500 psi	Pull-out	2280	0.62	2710	0.79	19%	27%
V	2 #10 Bars, Bond Length = 3.81", f'_c = 3500 psi	Pull-Out	1480	0.58	2435	0.70	-	21%
IV	2 #14 Bars, Bond Length = 5.07" f'_c = 3500 psi	Pull-out with Splitting	1530	0.50	1940	0.57	27%	14%

The increase in the bond strength under dynamic loading, observed in this test program, should be considered as an increase in the material property under rapid strain rates, because no substantial inertial effects were present. The absence of the inertial effects was confirmed from the measurements of the acceleration of most of the specimens. These measurements showed that the acceleration of the test specimen was quite small. The maximum acceleration of the test specimens of Type I, III, V was of the order of 5g, while the value of the maximum acceleration for Type II and IV specimens was about 2g and 6g respectively. (note that the mass of the test specimen is about 450/g.).

In Table 5.1, the percentage increase in "u" under dynamic loading, for Type III specimens, is omitted, because of the wide variation in f_c' of the static and dynamic test specimens. Also for the same reason, the percentage increase in "u" under dynamic loading, for Type V specimens is not shown in Table 5.2.

CHAPTER 6

CONCLUSIONS

Based on this research program, the following conclusions can be drawn:

1) The static ultimate bond strength of concrete for the relatively larger diameter reinforcing bars is of the order of 0.5 to 0.6 f_c', while the corresponding ultimate dynamic bond strength of concrete varies from 0.6 to 0.9 f_c', depending upon the compressive strength of concrete.

2) The static and dynamic ultimate bond stress "u" increases with the increase in f_c'.

3) The ratio u/f_c', for the values of f_c' between 2000 and 6000 psi is more or less constant for static case. This suggests that the ultimate bond stress is proportional to f_c' for the static case. In dynamic case, however, the corresponding u/f_c' ratio is not constant. The value of u/f_c' is much higher for the low strength concrete than for the high strength concrete.

4) The increase in the bond strength under dynamic loads is higher for the low strength concrete compared to the moderate or high strength concrete.

5) In both the static and dynamic case, the ultimate bond stress decreases with the increase in the diameter of reinforcing bars.

6) The increase in the ultimate bond strength under dynamic loads seems to vary inversely with the diameter of reinforcing bars.

APPENDIX I

BOND BEHAVIOR OF REINFORCING BARS IN PULL-OUT AND BEAM TEST SPECIMENS

Here, a brief summary of the literature on the bond behavior of reinforcing bars, tested in pull-out tests as compared to beam tests, is given. The purpose of this, is to illustrated the validity of pull-out tests in representing with reasonable accuracy, the bond conditions in the reinforced concrete elements, where bending is of the primary importance.

Initially, it appears that beam tests are better, because they represent more closely the bond behavior of reinforcing bars used in structural elements such as beams, beam columns, or retaining walls, etc., where the shear stresses have to be taken by the bond between concrete and reinforcing steel. Pull-out or push out tests, on the other hand, will closely represent the bond behavior of reinforcing bars, used for anchorage purposes. However, it is believed that this is not really so. The following points will illustrate the relative validity of pull-out or push-out tests in representing the bond behavior of reinforcing bars in flexural elements.

1) Most of the investigators who have previously carried out bond studies on beam and pull-out specimens report that there is a close correlation between the behavior of bars in these two types of specimens. On this point, R. M. Mains(8) who conducted a number of bond tests on pull-out and beam specimens gives the following observations from his tests.

(a) Plain bars without hooks, both in pull-out and in beam specimen failed in bond by excessive slip of the bars at the loads between one third and two thirds of the yield strength of bars. While deformed bars without hooks failed by the fracture of bars rather than bond failure.

(b) For plain hooked bars, failure was due to the fracture of bars in both types.

(c) There is a close similarity in the behavior of the portion of a beam bar between the free end and the nearest crack and the portion of the pull-out bar between the free end and a point on the bar, the same distance from the end as the crack in the beam.

A. P. Clark[7] who also conducted a number of tests on beam and pull-out specimens reports as follows.

"The correlation between the results of the beam and the pull-out tests was such as to indicate that pull-out tests can give reliable estimates of the bonding efficiency of deformed reinforcing bars. Although the data obtained from the two types of specimens did not always rate the bars in the same order, the difference in the ratings were usually too small to be of practical significance; moreover the relation between load and slip were of similar form and the general behavior of the bars was similar in two types of tests".

A similar correlation between the pull-out and beam tests is also found from the tests, reported in[12] where the results of a number of tests on the pull-out and beam specimens are given.

2) The distribution of bond stresses in the beam specimens largely depends upon the first crack and subsequent crack formation. R. M. Mains[8] who also conducted tests on the beams with controlled crack location; reports that distribution of bond stresses along the bar and the modifications introduced in the distribution of bond stresses due to cracks, are similar to these theoretically discussed by Mylrea[6]. Thus given the load and crack pattern for a beam it is possible to sketch the qualitative bond stress curves. However, it is felt that information obtained from such beam tests will not be very useful, because in the actual reinforced concrete structural members, it is quite difficult to predetermine the crack pattern. Therefore it is believed that, the beam tests will not be any better than the pull-out tests.

3) It is also established from the tests, made by different investigators that, though the basic set up is different in two types of tests, the influence of different parameters such as bar diameter, embedment length, strength of concrete, etc., on the bond behavior of reinforcing bars is not different. For example, if one parameter tends to increase the bond

resistance in beam tests, it also does so in pull-out tests. In the support of this point, the following observations are quoted from the tests reported[12].

(a) For both the pull-out tests and the beam, the bond resistance is slightly higher for stronger concrete both at the first slip and at the maximum load.

(b) For both the pull-out tests and the beams the ratio of unit bond resistance to compressive strength decreases as the strength of concrete increases.

(c) The effect of the length of embedment, on unit bond stress is similar in both pull-out and beam specimens. (This is very clearly indicated in Ref. 8, by the curves plotted for the length of embedment to diameter ratio versus unit bond stress for both the pull-out and the beam specimens).

4) There is one dissimilarity in two types of tests; in pull-out specimens concrete surrounding the bar is in compression, while in beam specimens, concrete surrounding the bars is in tension. However, this factor does not seem to alter the bond behavior of bars in two types of specimens, because even with this factor present in all the tests made on pull-out and beam specimens to determine the behavior of reinforcing bars in bond, a striking similarity is observed in the behavior of bars in both the specimens.

With these similarities and the correlation observed on the bond behavior of reinforcing bars in pull-out and beam specimens, it can be concluded that the pull-out specimens do represent with sufficient accuracy, the bond conditions in the reinforced concrete elements, where bending is of the primary importance.

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